Perspective

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Premature rejection in science: The case of the Younger Dryas Impact Hypothesis

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Abstract

The progress of science has sometimes been unjustifiably delayed by the premature rejection of a hypothesis for which substantial evidence existed and which later achieved consensus. Continental drift, meteorite impact cratering, and anthropogenic global warming are examples from the first half of the twentieth century. This article presents evidence that the Younger Dryas Impact Hypothesis (YDIH) is a twenty-first century case.

The hypothesis proposes that the airburst or impact of a comet ∼12,850 years ago caused the ensuing ∼1200-year-long Younger Dryas (YD) cool period and contributed to the extinction of the Pleistocene megafauna in the Western Hemisphere and the disappearance of the Clovis Paleo-Indian culture. Soon after publication, a few scientists reported that they were unable to replicate the critical evidence and the scientific community at large came to reject the hypothesis. By today, however, many independent studies have reproduced that evidence at dozens of YD sites. This article examines why scientists so readily accepted the early false claims of irreproducibility and what lessons the premature rejection of the YDIH holds for science.

Keywords

Younger Dryas, history of science, premature rejection, Impact Hypothesis, replication

Introduction

Scientists have initially rejected many theories that later achieved widespread consensus. In some instances, the rejection lasted for half a century or more, until enough new evidence arrived to convert all but the most obstinate opponents, who often carried their opposition to the grave.[1] The canonical example in the earth sciences is continental

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drift. First proposed by Alfred Wegener in 1912, continental drift did not achieve consensus until the mid-1960s.[2] The theory of meteorite impact cratering on the Moon and the Earth provides another example. We can date its origin to a classic 1893 paper by the great American geologist G. K. Gilbert[3] and the beginning of its broad acceptance to 1964 and the first returned photographs of lunar craters from the Ranger missions to the Moon. Both rejections stemmed mainly from the allegiance of geologists to the principle of uniformitarianism, which eschewed catastrophic events such as moving continents and colliding meteorites. Anthropogenic global warming offers a third example. First proposed by Svante Arrhenius in 1896, within a few years it had become almost universally rejected, based on a single, misinterpreted experiment.[4] Its acceptance began with the first results of computerized climate modeling in the mid-1960s. The pioneer of climate modeling, Syukuro Manabe, won the 2021 Nobel prize in physics for his early work. Today we can only wonder what the effect would have been had scientists in the first half of the twentieth century retained AGW as a working hypothesis.

One would hope and expect that in the internet age, with its online journals, instant communication, and vastly improved scientific methods and instrumentation, premature rejection would be a thing of the past. The reaction to the Younger Dryas Impact Hypothesis (YDIH), introduced in 2007, shows that this assumption is incorrect.[5] Within months of its appearance, two authors[6] called the hypothesis a “Frankenstein Monster” and in 2011, the same two plus others[7] compared it to UFOs and other examples of “pathological science” and wrote its “requiem.” Yet after a comprehensive review of the literature in 2021, Sweatman[8] concluded: “Probably, with the YD impact event essentially confirmed, the YD impact hypothesis should now be called a ‘theory’.” The question this article seeks to answer is how scientists can so thoroughly reject a hypothesis, even write its requiem, only to have it emerge in little more than a decade strengthened and deserving of possible promotion to the status of theory.

The Younger Dryas (YD)

The last great Northern Hemisphere ice sheet began to grow ~115 ka (thousand years ago) at the end of the last interglacial and by ~26.5 ka, had reached its maximum size and extent. Then ~20 ka, increasing solar insolation due to changes in the Earth’s orientation and position in space (the Milankovitch cycles) caused the great ice sheets to begin to melt and recede. At 12.85 ka, the warming ended and the temperature suddenly plummeted back to near-glacial frigidity, where it remained for ~1200 years until the warming resumed.

Scandinavian scientists at the turn of the nineteenth century named the cool period the “Younger Dryas” in honor of *Dryas octopetala*, a plant of the Arctic tundra that flourished under the return of near-glacial temperatures. Scientists used the term “Younger” to distinguish it from the Oldest Dryas, an earlier time in which the plant had also flourished. The last major glacial period had experienced some 25 short-term climate alternations, but the YD cool episode differed from them not only in timing but also in behavior.

One such difference was that although the Pleistocene temperature oscillations were geologically rapid, the onset and the termination of the YD were even more abrupt. “Within a single year or less,” the temperature of central Greenland fell by 9–14°C.[9] Then “In less than a few decades, and possibly in less than a few years,” temperatures rose by 5–10°C.[10]

Six major events occurred at or soon after the onset of the YD. For reference, the YD began 12.85 ka ± 0.14 years ago, as recorded in Greenland ice cores.[11]

1. Glacial Lake Agassiz was the largest of the "proglacial" lakes that formed across upper North America as glacial ice dammed streams and lake outlets. It covered several Canadian provinces and parts of the northern U.S. and was larger than the present Great Lakes combined. In glacial times this vast body of water drained south down the Mississippi River and into the Gulf of Mexico. Then as the Laurentide ice melted and retreated northward, the ice dams that had blocked the flow of water from Lake Agassiz failed catastrophically and new outlet channels opened, allowing the water to spill eastward through the St Lawrence system into the North Atlantic and northward down the Mackenzie River into the Arctic Ocean.[12] This "great plumbing shift," as geologists have nicknamed it, took place exactly at the onset of the YD.[12–15]
2. Murton et al.[16] and Keigwin et al.[12] dated the age of the Mackenzie River flood and thus the onset of the collapse of Lake Agassiz to shortly after 13 ka ago, at or near the beginning of the YD.
3. Another great ice sheet comparable to the Laurentide had covered Finland, Norway, Sweden, and part of Russia. As it retreated northward, the first catastrophic outburst flood from Baltic Ice Lake, a freshwater body that like Lake Agassiz formed from glacial meltwater, occurred at the YD onset at 12.85 ± 0.69 ka.[17]
4. The margins of the Greenland Ice Shelf began to destabilize "at the beginning of the Younger Dryas (12.8 cal. ka)."[18]

   Considering all of these events, Kennett[19] noted that "It is difficult to explain the triggering of such widespread synchronous changes at the margins of three relatively isolated Northern Hemisphere ice sheets: Laurentide, Fennoscandian, and Greenland, and their related proglacial lakes by invoking conventional climatic and/or paleoceanographic processes. Instead, this broad range of evidence is more readily explained by catastrophic processes triggered by a cosmic impact with Earth: the YDB cosmic impact theory."
5. In North and South America, about three-fourths of megafaunal mammal genera became extinct at or near the onset of the YD. Over the decades, anthropologists have debated rival theories to explain the extinctions: (1) slaughter of "naive" animals by newly arrived hunters (overkill); or (2) the climatic change that marked the arrival of the YD. However, extinctions on such a scale are not known to have occurred in association with other abrupt temperature oscillations of the Pleistocene. To illustrate how anomalous were the YD extinctions, consider the horse. In the Western Hemisphere, horses and their ancestors had survived as an unbroken evolutionary lineage for approximately 56 million years, since the beginning of the Eocene. Yet abruptly at or near the onset of the YD, every horse species outside Eurasia became extinct. As evidence that the onset of the YDB and at least some of the extinctions were virtually simultaneous, at some sites the so-named black mat, to be discussed later and which is synchronous with the onset of the YD, drapes over the bones of animals whose remains are never found in younger strata.
6. At the onset of the YD, the beautiful, fluted projectile points of Clovis disappear from the archeological record. They have never been found in situ above the

> YDB. Anderson et al.[20] present evidence that the population of Clovis also underwent a major decline. The people themselves did not disappear but likely transitioned from a continent-wide culture to dispersed regional societies.

One reason scientists have had difficulty settling on the cause or causes of the extinction and the disappearance of the Clovis toolkit is that they have been unable to reach consensus on the cause of the YD cooling itself. As W. H. Berger[21] summed up in 1990: “The origin of the Younger Dryas is likely to remain an enigma for some time to come, perhaps forever. If the cold spell resulted from an interplay of positive feedback mechanisms within the climate system, it will not be possible to distinguish cause and effect.” Perhaps the foremost student of the YD was the late Wallace Broecker, whose interest in this cool episode had begun with his PhD thesis. Shortly before Berger wrote the passage above, Broecker et al.[22] proposed what became the accepted hypothesis as the cause of the YD. Broecker and colleagues envisioned that the volume of meltwater exiting Lake Agassiz produced a cap of low salinity surface water over the North Atlantic and Arctic oceans, strongly reducing thermohaline circulation (sometimes referred to as the oceanic conveyor belt) that Broecker had discovered, leading to abrupt cooling of the adjacent continents.

However, the apparent lack of geomorphic evidence for the purported eastern drainage of Lake Agassiz led Broecker[23] to abandon his own hypothesis, now saying that the YD “was likely triggered by a freak event rather than by something common to each glacial termination.” In 2010, he reversed direction, writing with colleagues: “Evidence from Chinese stalagmites suggests that, rather than being a freak occurrence, the Younger Dryas is an integral part of the deglacial sequence of events that produced the last termination on a global scale.”[24] As described below, Broecker would change his mind once again.

The YD literature is voluminous, with Broecker et al.[24] calling the period “the best studied of the millennial-scale cold snaps of glacial time.” The point of this much-abbreviated summary is simply to show that by the first decade of the twenty-first century, though the YD had come to be regarded as “the canonical abrupt climate change event,” scientists had not reached consensus as to its cause.[25] It was time for a novel idea.

The Younger Dryas Impact Hypothesis

That the six events listed above happened at or close to the onset of the YD suggests that they may have had a single trigger. In 2007, Firestone et al.[5] proposed that “An extraterrestrial (ET) impact event at ∼12.9 ka (later recalibrated to ∼12.8 ka)…caused abrupt environmental changes that contributed to YD cooling, major ecological reorganization, broad-scale extinctions, and rapid human behavioral shifts at the end of the Clovis Period.” They posited that the impactor was “one or more large, low-density objects…most likely a comet.” Thus the YDIH proposes that an impact caused the YD cooling and was at least partly responsible for the megafaunal extinction and the Clovis cultural decline.

Firestone et al. presented chemical and physical evidence for the hypothesis from YD boundary (YDB) sites ranging across North America and one at Lommel, Belgium. Of the North American locations, one (Blackwater Draw, NM) is the Clovis type-site;

three have both human and megafaunal remains, suggesting they were kill-sites; and six have a "black mat" associated with the YDB. The black mat is an enigmatic, organic-rich layer found at approximately two-thirds of 97 YD geoarcheological sites in North America. Haynes equated the onset of black mat formation with the beginning of the YD.[26] He noted that "No skeletal remains of horse, camel, mammoth, mastodon, dire wolf, American lion, short-faced bear, sloth, tapir, etc., or Clovis artifacts have ever been found in situ within the YD age black mat, and no post-Clovis Paleoindian artifacts have ever been found in situ stratigraphically below it."

Scientists distinguish ET events from terrestrial ones by the distinctive set of markers that cosmic events leave behind. In the case of the Alvarez Theory of meteorite impact as the cause of dinosaur extinction, the first such marker to be discovered was a spike in the abundance of the rare metal iridium at the geological boundary (now called the K-Pg) at which the dinosaurs disappeared. Iridium is much more abundant in certain types of meteorites than in terrestrial rocks, hence the conclusion that its presence evinces an ET event. Iridium has since been found at dozens of other K-Pg boundary sites. It belongs to the platinum group elements, or PGEs, which also include osmium, palladium, platinum, rhodium, and ruthenium. I cover their occurrence at the YDB in a later section.

Microspherules with sizes in the range of a few tens of microns occur at the K-Pg boundary and at many known impact sites and represent another accepted marker. One difficulty is that terrestrial processes produce similar microspherules and the two cannot be distinguished by optical microscopy alone. However, using scanning electron microscopy (SEM) to reveal surface textures and X-ray fluorescence (XRF) to measure chemical composition, scientists can differentiate extraterrestrially formed microspherules from those exclusively formed by terrestrial processes.

Nano-sized diamonds have been found at the K-Pg boundary in Alberta, in the ~15 Ma Ries impact crater in Germany, and at the ~35 Ma Popagai impact crater in Siberia. Nanodiamonds thus provide another impact marker.

The most direct and diagnostic indicators of an ET event are minerals like quartz and zircon that have been shocked at the extreme pressures that in Nature only impact can produce. They are widespread at K-Pg boundary sites. Shocked quartz has not been corroborated at the YDB, but there have been a few tentative reports. Mahaney et al.[27] reported "planar deformation features (PDFs) in fine silt-size fragmental grains of quartz" in association with a proposed black mat layer of YD age in the Venezuelan Andes. In a later companion paper, Mahaney et al.[28] re-assessed this assertion, writing that they had "detected no *irrefutable* PDFs [or] shock-melted quartz [italics added]" at the Venezuelan site. Van Hoesel et al.[29] searched for shocked quartz at "multiple Ållerød-Younger Dryas boundary layers from Europe and North America," but found only one quartz grain with the diagnostic PDFs: at Usselo in the Netherlands. They suggested that "This grain was possibly eroded from an older crater or distal ejecta layer and later redeposited in the European sandbelt." A more intensive search for shocked quartz at the YDB is merited and is currently underway.[30]

As shown in Figure 1, Firestone et al. found "peak abundances" in the YDB of "(i) magnetic grains with iridium, (ii) magnetic microspherules, (iii) charcoal, (iv) soot, (v) carbon spherules, (vi) glass-like carbon containing nanodiamonds, and (vii) fullerenes with ET helium." That these markers rose to a peak right at the YDB was especially

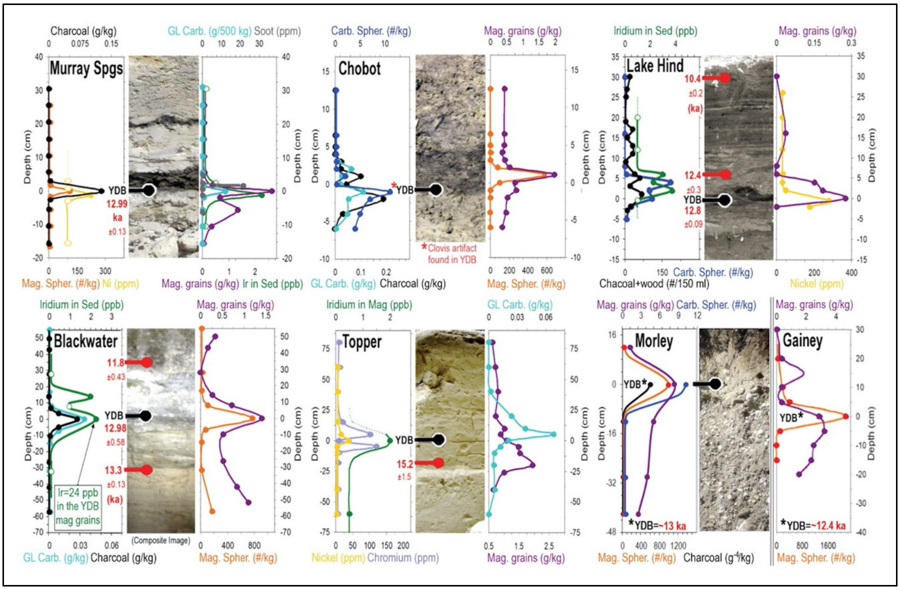


Figure 1. Event marker peaks at seven YDB sites.[5] With permission of the NAS. Copyright (2007) National Academy of Sciences, USA.

significant, as it suggested that they had been deposited in an extremely brief period. In this article, because of their importance in the history of the YDIH, I begin with the microspherules and nanodiamonds.

Extraordinary claims

In "Impacts, mega-tsunami, and other extraordinary claims," Pinter and Ishman[6] were the first to respond to Firestone et al. Their article appeared only four months later in the January 2008 issue of *GSA Today*, a widely read magazine for members of the Geological Society of America that presents "short, hot-topic, or issue-driven articles," to "promote greater influence of the earth sciences."

The first paragraph explained the title and set the stage:

> Recognition of the importance of impact cratering ranks among the most significant advances in earth and planetary sciences of the twentieth century, but recently there has been a proliferation of reports of impact events and sites that eschew simple, less spectacular alternative explanations. Here we focus on (1) Holocene-age ocean impacts and associated "mega-tsunami," and (2) a catastrophic impact event suggested at 12.9 ka. Carl Sagan once said that "extraordinary claims require extraordinary evidence"; we argue that these impacts do not meet that standard.

"Mega-tsunami" refers to putative enormous ocean waves that some believe caused the huge, chevron-shaped dune deposits found in Egypt, Long Island, Madagascar, the windward Bahamas, and a few other places. Some have attributed them to impact-generated tsunami, others to wind action. Whatever their origin, the chevrons have nothing to do with the YDIH.

The demand for extraordinary evidence goes back to Thomas Jefferson and to Laplace, who wrote, “The weight of evidence for an extraordinary claim must be proportioned to its strangeness.” Opponents of a hypothesis often cite the aphorism to call for additional evidence. But whether evidence is extraordinary is a matter of opinion, residing in the eye of the beholder. No doubt Firestone et al. would have said that the abundance peaks they reported did represent extraordinary evidence; Pinter and Ishman said the peaks did not, and this argument, like that regarding the chevrons, goes nowhere.

Firestone et al. raised two principal questions that any critic must address (1) Are the event markers ET?; and (2) How did they come to be concentrated at the YDB? To the first question, Pinter and Ishman answered: “Almost all of the material reported at 12.9 ka is ubiquitous throughout the geological record…This material results from the steady rain of micrometeorites through the atmosphere, the majority ablating and settling to the surface as dust.” Meteorite ablation is a well-known process that can produce nanodiamonds and round magnetic spherules, two of the markers that Firestone et al. reported. However, in continental deposits at the concentrations found by Firestone et al. microspherules and nanodiamonds have only been reported in large quantities when associated with widely accepted ET impact events.

Pinter and Ishman correctly noted that “Glassy spherules also derive from numerous anthropogenic processes and products.” Firestone et al. had investigated the possibility that the microspherules they discovered were terrestrial, noting that their YDB sites represented a variety of depositional environments, soil conditions, climate regimes, and biomes. The sites included coastal canyon deposits, arid-region streambeds, caves, lake and pond deposits, as well as glacial moraines and drumlins. The differing geologic processes that gave rise to these dissimilar deposits could hardly have produced identical microspherule peaks, especially not on the short time scale of the YDB. Moreover, Firestone et al. analyzed the microspherules using SEM and XRF and found that their surface features and chemical compositions were consistent with origin in an ET impact event, but not with a terrestrial one. More on this important point later.

A “steady rain” of meteoritic dust would not produce abundance peaks, so that the Pinter and Ishman model required a secondary process to concentrate them. There are two possibilities: (1) a temporary hiatus in deposition allowed a greater concentration of meteorite fallout to accumulate; or (2) an interval of erosion removed the lighter material and left behind the denser meteorite fragments. Both fail because the length of time represented by the YDB is far too short: at the Blackwater Draw, NM site, the type-site for the Clovis culture, Haynes et al.[31] concluded that any hiatus in YDB sedimentation lasted “probably no more than a decade and possible (sic) much less, that is, geologically instantaneous.” Remember, the entire YD lasted no more than ∼1200 years, an eyeblink of geologic time.

Another argument against the claim that the peaks derive from normal geological processes is that, as Firestone and West[32] pointed out: “Except for small quantities of magnetic grains and charcoal, the markers were undetectable in the sediment either above or below the impact layer, representing stratigraphic sequences spanning >55 k.y." In other words, except at the YDB itself, the key event markers were not present in sufficient quantities to be concentrated by any process.

As noted above, Firestone et al. had reported "fullerenes with ET helium" at three YDB sites. Fullerenes are spherical arrangements of dozens of carbon atoms in the shape of the geodesic dome made famous by architect Buckminster Fuller. Known as "Bucky-Balls," they have been found in the Allende and Murchison meteorites and also in the Cretaceous-Paleogene (K-Pg) boundary sedimentary deposits that mark the disappearance of the dinosaurs. Thus fullerenes appear to be a legitimate indicator of an ET event.

Pinter and Ishman wrote: "[F]ullerenes enriched in 3He" (Firestone et al. 2007c; Becker et al. 2007) are consistent with micrometeorite ablation fallout, although it must be noted that the fullerene and helium signals have been repeatedly characterized as nonreproducible," citing four references. This statement gives the impression that the fullerenes reported by Firestone et al. had been shown to be irreproducible, but none of the four references Pinter and Ishman cited has anything to do with the YDB and a literature search finds no other attempts to replicate the finding of YDB fullerenes. Thus the YDB fullerenes stand unchallenged by evidence. In any event, they are not critical to the YDIH itself.

Pinter and Ishman offer several criticisms having to do with the provenance of the hypothesis, the exact nature of the cosmic event, and the identity of the impactor itself [paragraph breaks added for clarity]:

> The 12.9-ka impact story has struggled to bring its disparate evidence under a single umbrella. The impact story originated in Firestone and Topping (2001) and the Firestone et al. (2006) book, both of which contain observations and claims so wild that other work by these authors invites careful scrutiny.
>
> The nature of the 12.9-ka event changes radically with each iteration, from a supernova-generated "cosmic ray jet"…to a massive atmospheric airburst…to "multiple ET airbursts along with surface impacts…." Airbursts are a convenient explanation, given the lack of an impact crater, tektites, shocked quartz, or high-pressure minerals.
>
> The 12.9-ka impact story also has struggled with the broad range of impact-related materials reported…. Any one of these [chondrite, iron-rich, stony, carbonaceous, lunar] might be a credible extraterrestrial source, but together they are a Frankenstein monster, incompatible with any single impactor or any known impact event.

But of course scientists modify hypotheses as new evidence comes to light and new models replace those that do not fit the new facts: this is how good science progresses, not a bug but a feature.

To sum up, Pinter and Ishman presented no new evidence, appealed to irrelevant arguments (the mega-tsunami and extraordinary evidence), and suggested processes to explain the abundance peaks that would have taken far longer than the decade or less that Haynes et al. said was possible. A reasonable conclusion would have been to call for scientists to reserve judgment on the YDIH and to seek additional evidence. Instead, Pinter and Ishman closed with this paragraph:

> Both the 12.9-ka impact and the Holocene megatsunami appear to be spectacular explanations on long fishing expeditions for shreds of support. Both stories have played out primarily in the popular press, highlighting how successful impact events can be in attracting attention. The desire for such attention is understandable in an environment where science and scientific funding are increasingly competitive. The National Science Foundation now emphasizes "transformative" research, and few events are as transformative as an impact. In an era when evolution, geologic deep time, and global warming are under assault, this type of "science by press release" and spectacular stories to explain unspectacular evidence consume the finite commodity of scientific credibility.

Let us pick apart this statement to see how well it holds up to careful scrutiny:

- "Long fishing expeditions": This implies that Firestone and colleagues chose the impact hypothesis first, then sought evidence to support it. But it happened the other way around. As reported both in an article and in a book about the origin of the impact hypothesis, William Topping discovered microspherules in the tens of thousands at the Gainey, MI Clovis site, then joined with others to search for them at other Clovis sites around the US, and found them.[33,34] Pinter and Ishman were aware of this since they cite both the article and the book.
- "Shreds of support": no one could reasonably describe the evidence that Firestone et al. presented, summarized in Figure 1, as "shreds."
- "Played out primarily in the popular press" and "science by press release": Firestone et al. did not introduce their hypothesis in a press release, but rather in an article in one of the most prestigious scientific journals. After that publication, NOVA and National Geographic did cover the YDIH, but this is the kind of publicity scientists would normally welcome.
- "The NSF emphasizes 'transformative' research": This hints that Firestone et al. chose their topic not because the evidence led them to it, but simply to win funding. Deniers of anthropogenic global warming level the same duplicitous charge at climate scientists. Any research scientist knows this is absurd, as for one thing, it would not work.
- "Spectacular stories to explain unspectacular evidence": As quoted above, Pinter and Ishman write that "Recognition of the importance of impact cratering ranks among the most significant advances in earth and planetary sciences of the twentieth century." Thus to invoke meteorite impact does not represent an appeal to the spectacular, but to a well-accepted process. Many might well regard the YDB abundance peaks as spectacular, though like the term extraordinary, this is in the eye of the beholder.
- "Consume the finite commodity of scientific credibility": This baffling statement seems intended to discourage further research on the YDIH.

Like all scientists, geologists have all they can do to keep up with the ever-increasing literature in their own field. For them, the Firestone et al. article in *PNAS* would have been optional reading, making it likely that the Pinter and Ishman article in *GSA Today* would have been the first time they encountered the YDIH. Finding the hypothesis scorned and ridiculed in a peer-reviewed article would have given them little reason to consider it again.

An independent investigation

The first clue that an ET event might have occurred at the onset of the YD, as noted above, was the discovery of seemingly exotic microspherules at the Gainey, MI Clovis site and several others.[33] The magnetic microspherules still rank as among the most important evidence for the hypothesis. Before proceeding, let us take a closer look at the sampling and laboratory methods that Firestone et al. used to collect and identify ET microspherules. Table 1 summarizes their results.

For reasons that will become apparent, two of the sites merit special attention: Blackwater Draw, NM, and Topper, SC. Blackwater Draw lies near the Texas border, 11 miles south of Clovis, NM, which gave its name to the distinctive projectile points found at the site. Blackwater Draw is critically important to both archeology and geology because the black mat, which is coeval with the onset of the YD, rests atop Clovis artifacts and the bones of butchered mammoths. Figure 1 from Firestone et al. shows that they sampled immediately below the black mat at Blackwater Draw. The YDB there had previously been dated to the same age as the boundary in the Greenland ice cores.[5]

Figure 2 is a photograph from Firestone et al. of a typical microspherule from Blackwater Draw (a) and ones from three other YDB sites. This evidence shows that at the YDB at Blackwater Draw and these other sites, Firestone et al. observed, counted, and photographed microspherules.

The Topper site resides on a high bank of the Savannah River near Allendale, SC. This Clovis-age stone quarry contains thousands of artifacts and has been described as "the jewel of Southern quarry-related Clovis sites."[36] Firestone et al. wrote of their sampling at Topper:

Table 1. Number of microspherules/kg and presence of the Black Mat for the seven sites shown in Figure 1.

Site	#MS/kg	Black Mat
Blackwater Draw	768	Yes
Chobot	578	Yes
Gainey	2144	No
Lake Hind[1]	No	Yes
Morley	1020	Yes
Murray Springs	109	Yes
Topper	97	No

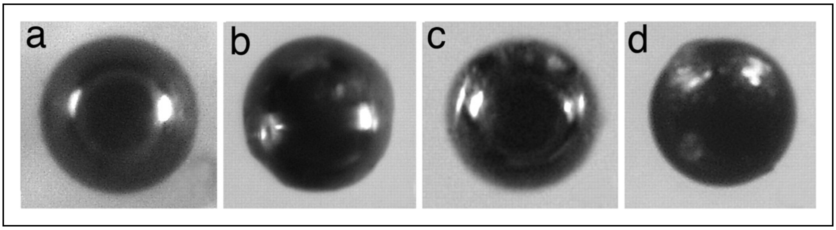


Figure 2. Microspherules from Blackwater Draw, NM (a); Chobot, AB, Canada (b); gainey, MI (c); and Howard Bay, NC (d). They range in size from 90–150 microns.[5] With permission of the NAS.

> At a new excavation, we used the neodymium magnet and a magnetic susceptibility meter to help identify the YD layer based on the high iron content. Shortly afterward, the excavators recovered part of a Clovis point immediately beneath the YD layer, illustrating the usefulness of the YDB markers for locating the Clovis horizon in new locations.

Firestone et al. found an abundance peak of 97 microspherules per kilogram at Topper, "within a ≈5-cm interval immediately in and above a distinct layer of Clovis artifacts." (See Figure 4 for a photograph of a microspherule from Topper.)

Firestone et al. described their sampling and analytical methods both in their article and in Supplemental Information, confirming that they used SEM/XRF to distinguish ET microspherules from terrestrial ones. They found that the chemistry of the microspherules is consistent with them being melted terrestrial sediments rather than impacted volcanic rocks.

From the article:

- "When YDB microspherules were analyzed by SEM/x-ray fluorescence and compared with known cosmic and volcanic microspherules, they appear to be nonvolcanic in origin."
- "Microspherules, glass-like carbon, and carbon spherules were analyzed by SEM/x-ray fluorescence. These methods are very standard and discussed further in SI Text."

From Supplemental Information:

- "These spherules were either left whole or sectioned and given a microprobe polish for analysis by laser ablation or x-ray fluorescence (SEM/XRF)."
- "Representative microspherules were sliced, polished, and mounted for analysis by XRF with a scanning electron microscope (SEM)."

It is important to emphasize that Firestone et al. found that rather than being elevated across the YDB but randomly distributed, the microspherules reached abundance peaks at Blackwater Draw, Topper, and the other sites listed in Table 1. The existence of the peaks has special significance. First, the finding of similar abundance peaks at sites with different geological provenances makes it unlikely that terrestrial processes were their cause. Second, the finding of peaks at multiple sites replicated the YDB microspherule evidence and showed that it was not a fluke of a single site. Conversely, at no site (save initially at Lake Hind) did Firestone et al. search for microspherules and fail to find them. Third, the peaks record a short-lived event synchronous across North American sites and one in Europe. Meteorite impact and volcanism are the only two candidates as the cause of such rapid processes with such widespread effects. Fourth, Firestone et al. first located and sampled the YDB, then found the same anomalous peaks at each site. This is evidence that they did indeed sample the boundary layer and not some other. Fifth, errors by Firestone et al. in their sampling or procedures would have destroyed existing peaks and could not have produced them.

Pinter and Ishman did not question whether the microspherules and their peaks existed, only whether they were ET. But in October 2009, a group reported that they had been unable to replicate the YDB microspherule evidence. The lead author of "An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis" was Todd Surovell of the Department of Anthropology at the University of Wyoming.[37] The final two sentences of the abstract read:

> Herein, we report the results of an independent analysis of magnetic minerals and microspherules from seven sites of similar age, including two examined by Firestone et al. We were unable to reproduce any results of the Firestone et al. study and find no support for Younger Dryas extraterrestrial impact.

Figure 3 summarizes the results of the Surovell et al. study; henceforth I will focus on the "magnetic spheres," which came to be called microspherules.

At four of their YDB sites, Surovell et al. found microspherules but no peaks and at three—Paw Paw Cove, Topper, and Shawnee-Minisink—found no microspherules at all. At the four sites where they did find microspherules, shown in black in Figure 3, the pattern of vertical distributions differs from site to site. This not only casts doubt on the putative origin of the microspherules in a single, virtually instantaneous event but is hard to explain by any conceivable process.

In their supplemental information, Firestone et al. wrote that at Blackwater Draw "YDB markers are concentrated in a ~2-cm layer of fine-grained fluvial or lacustrine sediment that lies at the base of the black mat in the uppermost stratigraphic horizon containing in situ mammal bones and Clovis artifacts." As shown in Figure 1, it was from this layer that they recovered, counted, and photographed microspherules—one of which is shown in Figure 2. Above and below the YDB layer, Firestone et al. found no microspherules. Using SEM and XRS, they identified the microspherules at Blackwater Draw as of ET origin.

Since Firestone et al. showed dispositive photographic evidence that the microspherules exist at the YDB at Blackwater Draw and the other sites, we can only conclude that Surovell et al. failed to sample the YDB and/or erred in their procedures. When dealing with objects on the scale of tens of microns, avoiding such errors requires punctilious care.

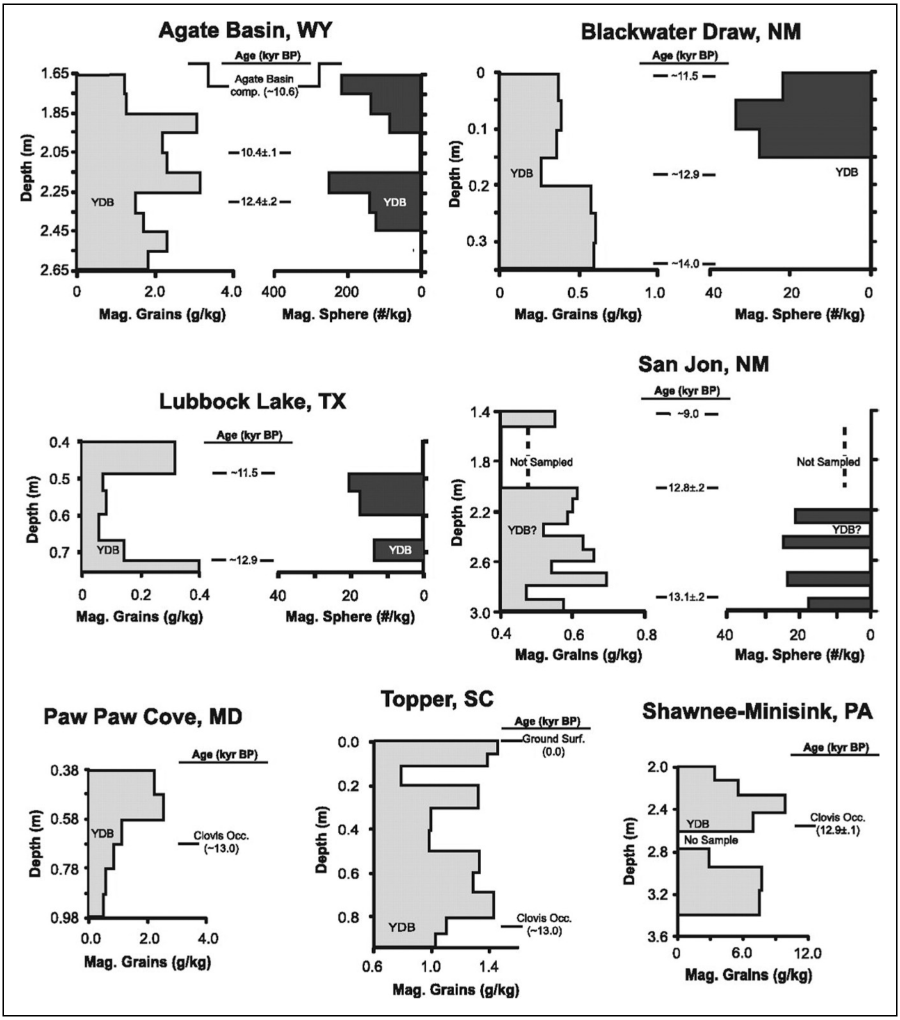


Figure 3. Concentrations of magnetic grains and microspherules from seven YDB sites across North America.[37] With permission of the NAS.

What can we say of the microspherules that Surovell et al. did find above the YDB at Blackwater Draw? There are two possible explanations: (1) they are terrestrial, or (2) they are ET but have been eroded from the YDB and redeposited into the sediments above. We cannot decide between the two because, though Firestone et al. repeatedly specified the need to use SEM and XRF to distinguish the two types, Surovell et al. used neither method.

At Topper, where Firestone et al. found 97 microspherules per kilogram of sediment, Surovell et al. found no microspherules at all. The photograph in Figure 4 is dispositive evidence of the presence of microspherules at Topper. The simplest explanation is again that Firestone et al. sampled the YDB at Topper while Surovell et al. did not. The Topper site does not have the black mat or anything else to mark the boundary to the eye, so researchers could miss it. Surovell et al. write, "Limited chronological control is available beyond the presence of time-diagnostic cultural materials. In our sample column, the Clovis component occurs at a depth of ∼80–90 cm beneath the surface, and, like Firestone et al. we *assume* that the YDB falls within this interval [italics added]."

As with Blackwater Draw, another possibility is that Surovell et al. did sample the YDB at Topper, but made some error or errors in sample preparation and analysis that caused them to lose or fail to observe microspherules.

The point here is not to try to identify specific errors that Surovell et al. might have made, but to note that such errors can explain why they found no microspherules at all at Topper and only ones above the YDB at Blackwater Draw. But as noted, errors *cannot* explain the microspherule peaks reported by Firestone et al.

The least appropriate response to these contradictory results would have been to declare that the absence of evidence reported by Surovell et al. should trump the positive, physical, and even photographic evidence reported by Firestone et al. Surovell et al. should have declared the matter unsettled and called for more research, including blind tests, sample exchange, and the like. Indeed, toward the end of their article, they seemed to verge on this conclusion:

> Assuming an ET impact occurred, perhaps the lack of reproducibility indicates that the methods used for recovering the magnetic material are not appropriate for the task at hand. Recognition and identification of the spherules is especially difficult and somewhat subjective.

But instead of resting their case with this sound scientific statement and keeping the door open for the YDIH, Surovell et al. instead slammed it shut by writing:

> Replicability is fundamental to the scientific method and hypothesis testing; results that are not reproducible cannot be considered reliable or supportive of a hypothesis.

> In short, we find no support for the extraterrestrial impact hypothesis as proposed by Firestone et al.

These two statements taken together in effect say that the YDIH microspherule evidence is irreproducible. But it should have been obvious that Surovell et al. had not established that, only that *they* were unable to reproduce the evidence, for whatever reason. The possibility if not the near certainty that it was Surovell et al. who had erred should have caused scientists to reserve judgment about the YDIH. Instead, as shown in Table 2, right up to the present day many scientists have embraced the results of Surovell et al. to cast doubt on the hypothesis.

Table 2. Articles citing Surovell *et al.* as the basis for the quotation.

Quotation	Source	Year
The Firestone et al. impact-marker records have not proven reproducible in a subsequent study.	Carlson[38]	2010
Many of the impact markers reported in YD black mats have been widely discredited.	Daulton[39]	2010
Other studies have been unable to duplicate the evidence presented in support of a YD impact.	Scott[40]	2010
An independent study has been unable to confirm the presence of peaks in the contents of magnetic grains and magnetic spherules at the YD boundary.	French and Koeberl[41]	2010
Although some geological evidence is offered on its behalf strong counterevidence also recently appeared.	Holliday[42]	2010
All attempts to test and replicate this claim or to confirm aspects of this hypothesis have not been successful, raising serious concerns about the veracity of the claim.	Holliday[43]	2011
Reported measurements of unique peaks in concentrations at the YD onset have yet to be reproduced.	Pinter[7]	2011
Magnetic microspherule abundance results published by the impact proponents have not been reproducible.	Boslough[44]	2012
Samples collected by [someone other than Firestone et al. co-author Allen West] have failed to reproduce his findings.	Boslough[45]	2013
Results of physical and geochemical analyses used to support the YDIH have failed or show that many indicators are not unique to an impact nor to (12.9 ka).	Holliday[46]	2014
The reproducibility, reliability, and validity of the impact indicators have been challenged.	Meltzer[47]	2014
The evidence presented was either not indicative of an ET impact or not reproducible by other groups.	van Hoesel[48]	2014
Multifarious criticisms have been raised regarding the identification, analysis and interpretation of these materials as impact markers.	Daulton[49]	2017
Many of the proposed impact markers have been abandoned or rejected.	Daulton[50]	2017
Independent researchers have failed to identify the proposed impact proxies in YDB aged sediments.	Jorgeson[51]	2020
Surovell et al. failed to duplicate the magnetic grain or microspherule peaks associated with the YD basal boundary.	Sun[52]	2020
Reproducibility of these markers is challenged by failed duplication of proxy signatures at the same sites.	Sun[53]	2021

A requiem

In 2011, Pinter et al.[7] published "The Younger Dryas Impact Hypothesis: A Requiem." They began with a review of the YDIH and reported new results from the authors' study of two sites on the Channel Islands off Santa Barbara. The abstract concluded,

> In all of these cases, sparse but ubiquitous materials seem to have been misreported and misinterpreted as singular peaks at the onset of the YD. Throughout the arc of this hypothesis,

> recognized and expected impact markers were not found, leading to proposed YD impactors and impact processes that were novel, self-contradictory, rapidly changing, and sometimes defying the laws of physics. The YD impact hypothesis provides a cautionary tale for researchers, the scientific community, the press, and the broader public.

The samples studied by Pinter et al. were collected and described by Scott et al.[40] Pinter and colleagues used the same suite in research on nanodiamonds, discussed below. Pinter et al. write that they "completed spherule frequency analyses complementary to the work by Surovell et al." focusing on the Arlington Canyon site on Santa Rosa Island, where they said their sampling location was "identical or closely proximal to the location reported by Kennett." However, Wittke et al.[54] pointed out that,

> The published Universal Transverse Mercator coordinates [of Pinter et al.] reveal that their purported continuous sequence is actually four discontinuous sections. These locations range in distance from the site investigated by Kennett et al. by 7000 m, 1600 m, 165 m, and 30 m (SI Appendix, Fig. S1B), clearly showing that they did not sample the YDB site of Kennett et al. Furthermore, this sampling strategy raises questions about whether Pinter et al. sampled the YDB at all, and may explain why they were unable to find peaks in YDB magnetic spherules, carbon spherules, or nanodiamonds.

As further evidence of the point, Pinter et al. write that "No clear YDB 'marker bed' was present in any of our sections, so unlike Firestone and Surovell, our results focus on the distribution (and nature) of spherules through sediments pre-dating, dating to, and post-dating the onset of the YD." This is tantamount to saying that Pinter et al. did not sample the YDB on the Channel Islands. The two stratigraphic sections in their article (Figures 3 and 4), which show the depths at which samples were taken, confirm that they did not sample the YDB. Wolbach et al.[55] wrote that Pinter et al. "failed to sample the YDB age interval at all, resulting in a fatally flawed investigation. Although these authors acquired SEM images to support their argument, they presented no SEM images of melted, dendritic YDB spherules and instead showed only images of unmelted framboids and unmelted detrital grains. The lack of SEM imagery calls into question their negative conclusions."

Pinter et al. also took up the statement by Firestone et al. that in their YDB samples they had found "charcoal, soot, carbon spherules, and glass-like carbon, all of which suggest intense wildfires." To refute this claim, Pinter et al. cited the work of Marlon et al.,[56] who had used charcoal and pollen records from 35 sites to assess "how fire regimes in North America changed during the last glacial–interglacial transition (15 to 10 ka), a time of large and rapid climate changes." Marlon et al. also tested "the hypothesis that a comet impact initiated continental-scale wildfires at 12.9 ka," finding that "the data do not support this idea, nor are continent-wide fires indicated at any time during deglaciation."

Wolbach et al.[57] extended the work of Marlon et al. to report, "Quantitative analyses of charcoal and soot records from 152 lakes, marine cores, and terrestrial sequences reveal a major peak in biomass burning at the Younger Dryas (YD) onset that appears to be the highest during the latest Quaternary." Wolbach et al. summed up: "YDB peaks in charcoal and soot across four continents are synchronous with the ages of an abundance peak in platinum in the Greenland Ice Sheet Project 2 (GISP2) ice core and of the YDB impact event (12,835–12,735 Cal BP). Thus, existing evidence indicates that the YDB impact event caused an anomalously large episode of biomass burning, resulting in extensive atmospheric soot/dust loading that triggered an 'impact winter.'"

Pinter et al. ended with these statements:

> Research through the past century has documented the significance of extraterrestrial impact events in shaping the Earth's surface, climate, and life through geological time. A widespread problem, however, is that some researchers, when confronted with any unusual geological evidence, too readily jump aboard the "impact bandwagon."
>
> This review has been framed as a "requiem," suggesting the end of the YD impact hypothesis. It is fair then to ask whether we are indeed seeing the end of this hypothesis. As for some proponents, the answer is certainly 'no' — several have stated that they will continue their quest until the hypothesis is confirmed. Some insight is gained by adding a historical perspective here. Scientific hypotheses are constantly being proposed, tested, confirmed, or cleanly rejected, but a small minority of these stray from this time-proven path. Many scientists are unaware of the surprising number of hypotheses that have gone badly astray, often after widespread initial interest and support (Langmuir and Hall, 1989; Gratzer, 2000; Park, 2000). Characteristics of these wayward hypotheses include claims that are spectacular, data that are subjective or at the limit of precise measurement, and criticisms met with ad hoc excuses and/or shifts in the original claims (after Langmuir and Hall, 1989). We suggest that much can be gained by stepping back and looking at the broader lessons for the earth sciences, impact science, archeology, and other affected fields.

The three citations are to works titled, respectively: Pathological Science;[58] The Undergrowth of Science: Delusion, Self-Deception, and Human Frailty;[59] and Voodoo Science: The Road from Foolishness to Fraud.[60] The examples of pseudoscience discussed in these works include UFOs, cold fusion, perpetual energy, extrasensory perception, eugenics, the "Jewish Physics" of the Nazis, the Roswell UFO, homeopathy, the works of Deepak Chopra, animal magnetism and more.

The articles we have reviewed so far, especially given the language they used and their condemnatory conclusions, could not have failed to give readers the impression that the YDIH evidence was irreproducible and the hypothesis likely false, if not actually falsified, as the use of the word "requiem" suggests. But if the microspherule peaks do not exist, then how did Firestone et al. and later others, come to count and even to photograph them?

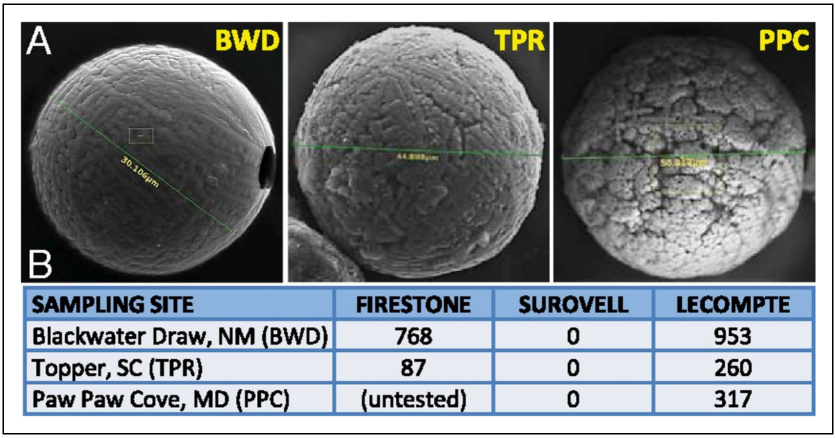
Microspherule findings replicated

LeCompte et al.[61] conducted an "independent blind investigation" of microspherules at the Blackwater Draw and Topper sites, as well as a third site at Paw Paw Cove, Maryland. Firestone et al. had not included the Paw Paw site in their study; Surovell et al. did include it but as shown in Figure 3, found no microspherules there. As illustrated in Figure 4, LeCompte et al. found "abundant YDB microspherules at all three widely separated sites consistent with the results of Firestone et al. and conclude[d] that the analytical protocol employed by Surovell et al. deviated significantly from that of Firestone et al." LeCompte et al. used SEM and XRF to show that the spherules were not "cosmic, volcanic, authigenic [formed in place], or anthropogenic in origin. Instead, they appear to have formed from abrupt melting and quenching of terrestrial materials."

At both Blackwater Draw and Topper, where Surovell et al. had found no YDB microspherules, LeCompte et al. directly replicated the findings of Firestone et al. At Paw Paw Cove, where Surovell et al. found no microspherules at any depth, LeCompte et al. found a peak at the YDB of 317 per kilogram. They identified several deficiencies in the methodology of Surovell et al.:

- Sample thicknesses too large, diluting the apparent abundance of the microspherules.
- Aliquots of the magnetic fraction 20–100 times smaller than those of Firestone et al. resulting in aliquots "of insufficient size to visually detect even a single spherule."
- Inadequate size-sorting. LeCompte et al. note that when they began their investigation, they "inadvertently failed to size-sort the magnetic fraction from sites." This caused them initially to find no spherules. However, when they "implemented rigorous size-sorting," they observed spherules in the same numbers as Firestone et al.
- Demand for perfect sphericity. Surovell et al. required that to be counted, a microspherule needed to appear perfectly spherical under the optical microscope. But Firestone et al. included microspherules that were less than perfect spheres, which many are (See Figure 6). This discrepancy alone would have caused Surovell et al. to report lower microspherule abundances.
- Most importantly, Surovell et al. performed no SEM or geochemical analysis by XRF, as required in the Firestone et al. protocol. "Without SEM imagery to examine their surface microstructure," LeCompte et al. wrote, "it is impossible to differentiate YDB magnetic spherules from those created by other natural or anthropogenic sources including framboids or rounded detrital magnetite, which, in our experience, often appear identical to YDB spherules under an optical microscope." They noted that the average chemical composition of the microspherules at Topper is "consistent with average percentages for sediment at the Earth's surface, indicating that these spherules formed from melted terrestrial surficial sediments." Such melting always occurs during a cosmic impact event.

Other researchers would later replicate the microspherule peaks reported by Firestone et al. and LeCompte et al. At the YDB at Blackwater Draw, Andronikov et al.[62] used SEM and XRF to find "abundant hollow magnetic microspherules that display dendritic surface textures," attributing them to "quenching during rapid cooling of molten material." They suggested that "Surovell et al. (2009) just failed to sample the microspherule-rich layer because it is visually featureless in the BWD-1 site and is very difficult to identify in the field."



SAMPLING SITE	FIRESTONE	SUROVELL	LECOMPTE
Blackwater Draw, NM (BWD)	768	0	953
Topper, SC (TPR)	87	0	260
Paw Paw Cove, MD (PPC)	(untested)	0	317

Figure 4. Images of YDB microspherules from three sites where Surovell *et al.* found none.[61] With permission of the NAS.

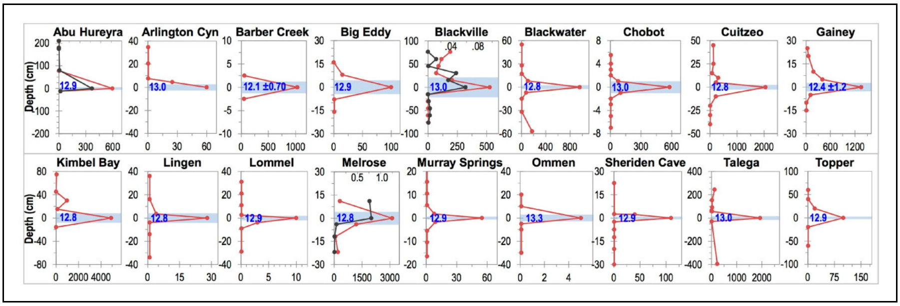


Figure 5. Abundances of microspherules (red lines) and SLOs (siliceous scoria-like objects) (black line) at 18 YDB sites.[54] The thickness of the sample used is indicated by the blue bar. Dates for the YDB layer are in blue. With permission of the NAS.

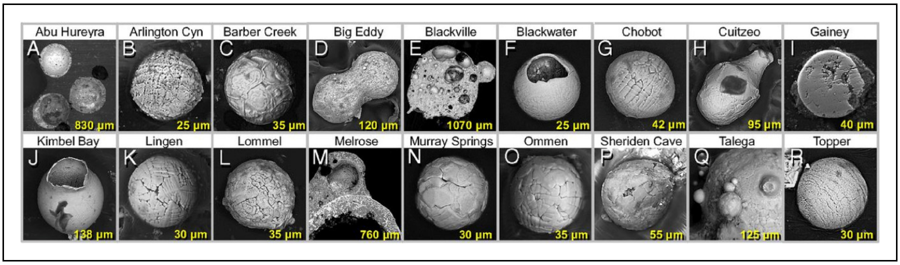


Figure 6. SEM images of microspherules from 18 YDB sites, illustrating the wide variety of sizes, shapes, and microstructures.[54] With permission of NAS.

Wittke et al.[54] reported the presence of microspherule peaks at 18 YDB sites on four continents, using SEM and XRF to identify them as ET (see Figures 5 and 6). They titled their article, “Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 y ago.” They found microspherule peaks at Blackwater Draw and Topper, where Surovell et al. had failed to find them, and at Arlington Canyon, where Pinter et al. had failed to locate the YDB.

By today, as shown in Table 4, researchers have directly replicated YDB microspherules at 13 sites: Abu Hureyra, Blackville, Blackwater Draw, Chobot, Gainey, Gull-Mt. Viso, Lake Cuitzeo, Lake Hind, Lommel, Melrose, Murray Springs, Sheriden Cave, and Topper. The early claims that the microspherules were irreproducible were false.

Nanodiamonds (ND)

Nanodiamonds measure only a few nanometers (10^{-9} m) in width and are invisible to the naked eye. Together with the microspherules, they provide some of the strongest evidence for an ET event at the onset of the YD. Firestone et al. reported that in the YDB sites they sampled, “Directly beneath the black mat, where present, we found a thin, sedimentary layer (usually <5 cm) containing high concentrations of magnetic microspherules and grains, nanodiamonds, iridium (Ir) at above background levels….” J. P. Kennett et al.[63] described nanodiamonds at three YDB sites: Lake Hind, Manitoba; Bull Creek, OK; and Murray Springs, AZ. D. J. Kennett et al.[64] reported, “shock-synthesized hexagonal nanodiamonds (lonsdaleite) in YDB sediments dating to ~12,950 ± 50 Cal BP at Arlington Canyon, Santa Rosa Island, California.”

Kurbatov et al.[65] reported “the discovery in the Greenland ice sheet [of] n-diamonds and hexagonal diamonds (lonsdaleite), an accepted ET impact indicator, at abundances of up to about 5×10^{6} times background levels in adjacent younger and older ice.” The age control needed to be improved, they noted, but “Using a preliminary ice chronology based on oxygen isotopes and dust stratigraphy, the ND-rich layer appears to be coeval with ND abundance peaks reported at (YDB) sites.”

Daulton et al.[39] examined carbon-rich materials isolated from the same suite of Channel Island samples as Scott et al.[40] and reported that “No nanodiamonds were found in our study. Instead…previous studies misidentified graphene/graphane-oxide aggregates as hexagonal diamond and likely misidentified graphene as cubic diamond. Our results cast doubt upon one of the last widely discussed pieces of evidence supporting the YD impact hypothesis.” But as we discussed earlier, none of the samples collected by Scott et al. came from the YDB, so that articles based on these samples cannot provide direct evidence for or against the YDIH. Microspherules and nanodiamonds investigated in studies based on the Scott et al. sample suite are, at best, of unknown origin.

Scott et al. also examined a single specimen from Murray Springs, AZ and found it to contain no nanodiamonds. But they wrote, they “did not carbon-date” the specimen, so there is no assurance that it came from the YDB. As noted above, Kennett et al.[63] found nanodiamonds at the YDB at Murray Springs.

Tian et al.[66] independently reported “cubic diamond nanoparticles in large numbers” at the YDB site at Lommel, Belgium, but Daulton et al.[49] were unable to replicate this finding. Israde-Alcantara et al.[67] described a site at Lake Cuitzeo in Central Mexico that dates to the early YD and has a black layer containing: “three allotropes of nanodiamond: n-diamond, i-carbon, and hexagonal nanodiamond (lonsdaleite), in order of estimated relative abundance.” Bement et al.[68] independently replicated the earlier finding of nanodiamonds at the Bull Creek site.

As shown in Figure 7, Kinzie et al.[69] extended these findings by reporting the presence of nanodiamond peaks “in 22 dated stratigraphic sections in 10 countries of the Northern

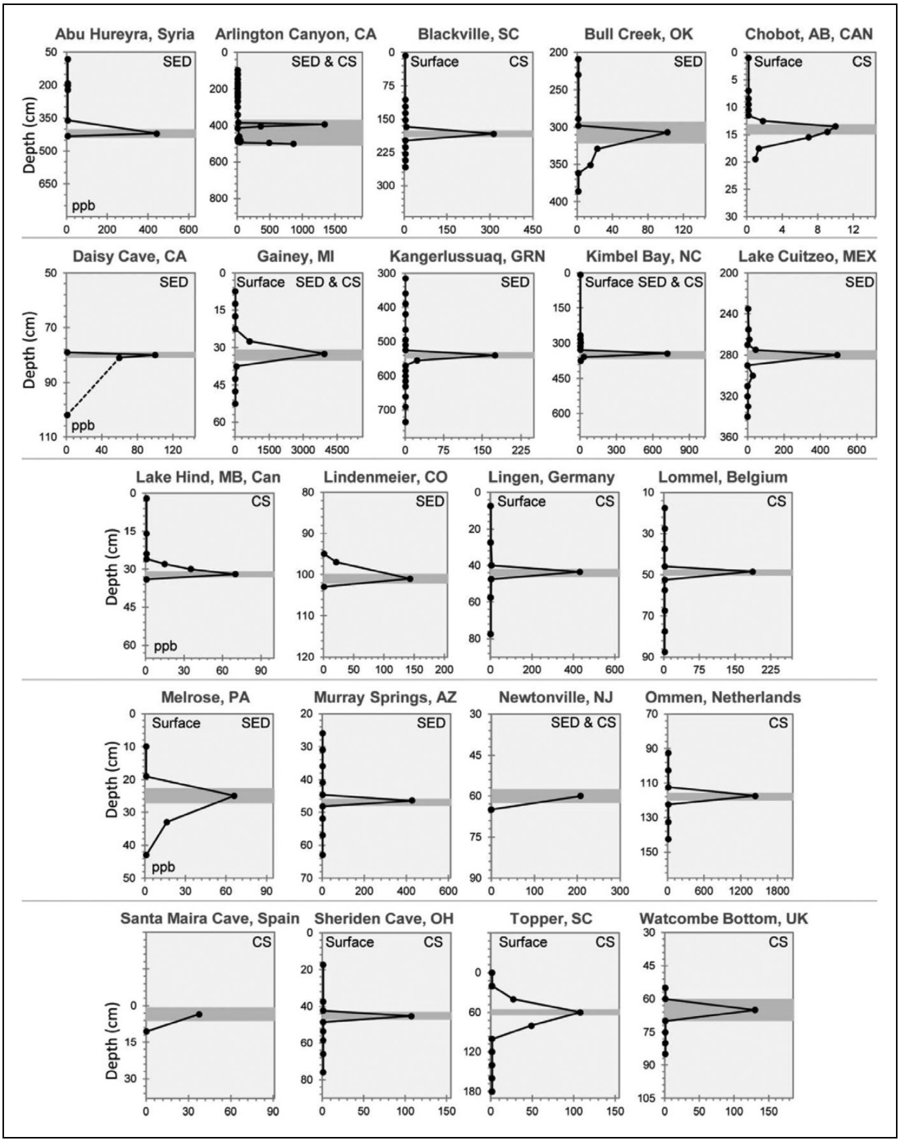


Figure 7. Nanodiamond abundance peaks at 22 YDB sites. Horizontal bands show the thickness of the samples that contain nanodiamonds.[69] CS = nanodiamonds from carbon spherules; SED = from bulk sediment. With permission of the Journal of Geology, University of Chicago.

Hemisphere." The types observed included "cubic diamonds, lonsdaleite-like crystals, and diamond-like carbon nanoparticles, called n-diamond and i-carbon." The nanodiamond abundances in bulk YDB sediments averaged 200 ppb and in carbon spherules, ~750 ppb. Carbon isotope ratios indicated that the nanodiamonds came from terrestrial carbon rather than from the impactor itself, as is typically the case in known impact events.

In a 2017 article titled, "Comprehensive analysis of nanodiamond evidence relating to the Younger Dryas Impact Hypothesis," Daulton et al.[49] isolated "Millimeter-scale carbonaceous spherules and/or their fragments…from Arlington Canyon, Santa Rosa Island, California, sediments…." They reported, "In no case were any of these nanocrystals found to be carbonaceous, and no nanocrystals of diamond were observed." But again, as we discussed for studies of the same suite by Scott et al.[40] and Pinter et al.,[7] none of the samples investigated came from the YDB layer.

By today, as shown in Table 4, scientists have directly replicated YDB nanodiamonds at 8 sites: Arlington Canyon, Bull Creek, Kangerlussuaq, Lake Cuitzeo, Lake Hind, Lommel, Murray Springs, and Sheriden Cave.

Platinum group elements

In their early critique of the YDIH, Pinter and Ishman wrote, "Siderophile elements, especially the platinum group elements (PGE), are significantly more abundant in meteorites than terrestrial upper crustal rocks. Their presence in sediments is one line of evidence unanimously accepted by impact researchers." In "The convincing identification of terrestrial meteorite impact structures: What works, what doesn't, and why," French and Koeberl[41] wrote, "The detection of anomalous excesses of Ir (e.g. ≥1 ppb) and other siderophile elements in the rocks of suspect structures can also provide convincing evidence of meteorite impact, but only if some additional criteria are met."

Iridium

Firestone et al. reported a modest iridium enrichment in YDB sediments and Kennett et al.[63] found "above-background iridium amounts at Lake Hind and Murray Springs." Haynes et al.[70] searched for iridium anomalies at Murray Springs, but found none. At the Lake Hind site, Paquay et al.[71] measured an iridium peak of 0.12 ppb and one of ~3 ppb for Pt, six times the crustal abundance of platinum. They interpreted the iridium peak to be the result of authigenesis (formation in place) rather than impact. At Hawks Tor in the southwest of England, Marshall[72] reported "an increase of over 300% in the iridium concentration compared with the values found below the [YDB]." At 10 of 13 black mat sites, Pigati et al.[73] "found elevated concentrations of iridium in bulk and magnetic sediments, magnetic spherules, and/or titanomagnetite grains within or at the base of black mats, regardless of their age or location." They wrote that this "suggest[ed] that elevated concentrations of these markers arise from processes common to wetland systems, and not a catastrophic ET impact event." Andronikov et al.[62] reported that four of six microspherules collected at Blackwater Draw had iridium concentrations ranging from 19 to 230 times crustal abundance. (Platinum in the suite varied from 36 to 920 times crustal abundance.) Teller et al.[35] replicated elevated iridium (and other impact proxies) at Lake Hind. At Abu Hureyra, Syria, Moore et al.[74] report an iridium anomaly in YDB meltglass.

As with the microspherules, these mixed results might have been worthy of an intensive effort to resolve, but instead another member of the PGE group became the focus of attention.

Platinum

Petaev et al.[75] measured the level of iridium and platinum at the YDB in the GISP2 ice core over the interval near the YD onset, with the results shown in Figure 8. They reported that:

> Pt concentrations gradually rise by at least 100-fold over ~14 y and drop back during the subsequent ~7 y. The decay of the Pt signal is consistent with the ~5-y lifetime of dust in the stratosphere. The observed gradual ingrowth of the Pt concentration in ice over ~14 y may suggest

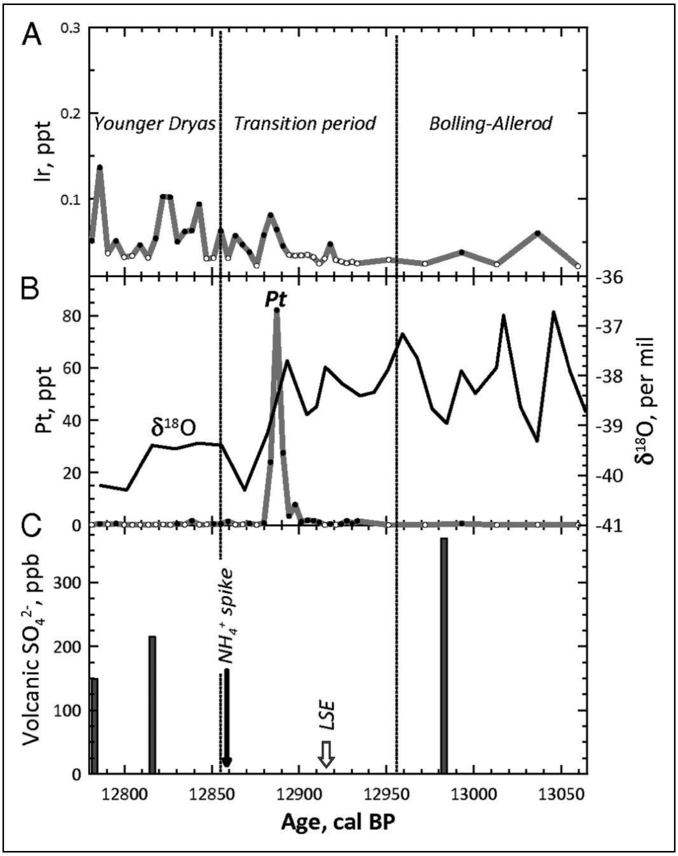


Figure 8. Iridium (A) and platinum (B) concentrations across the YDB in GISP2 ice samples. A large Pt spike coincides with a sharp drop in $\delta^{18}O$ at the onset of the YD. (C) Volcanic eruptions over the YDB interval. With permission of the NAS.

> multiple injections of Pt-rich dust into the stratosphere that are expected to result in a global Pt anomaly.
>
> The impact hypothesis, once declared dead, recently gained new support from the discovery of siliceous scoria-like objects (SLOs) with global distribution, which provide strong evidence for processing at high temperatures and pressures consistent with a cosmic impact.
>
> An extraterrestrial source of Pt appears likely.

In response to the suggestion of Petaev et al. that the platinum anomaly might be global, Moore et al.[76] tested for platinum at four well-studied YDB sites: Arlington Canyon, CA; Murray Springs, AZ; Blackwater Draw, NM; and Sheriden Cave, OH. At each, they found a platinum spike well above background coincident with microspherule and nanodiamond peaks, and in three cases, associated with Clovis artifacts, representing the level at which the Clovis culture disappeared (see Figure 9).

As a further test, Moore et al. expanded their search for the platinum peak to seven other YDB sites in the southeastern U.S. These are poorly or not directly dated and lack the black mat, but do provide a coherent Clovis archaeological record. Moore et al. found that although concentrations vary widely, at each of the seven sites a Pt peak coincided with the YD onset based on archaeostratigraphy and chronometric dates. Platinum averaged about 6.0 ppb, well above crustal abundance and hence consistent with the YDIH.

Moore et al. wrote,

> We expect the Pt anomaly to serve as a widely distributed time marker horizon (datum) for identification and correlation of the onset of the YD climatic episode at 12,800 Cal B.P. This Pt datum will facilitate the dating and correlating of archaeological, paleontological, and paleoenvironmental data between sequences, especially those with limited age control.

One of the few well-dated lake sediment cores, from White Pond in South Carolina, exhibits distinct platinum and Pt/Pd anomalies as well as a large soot peak dating to the YD onset.[77] Volcanic tephra, minute glassy objects produced by pyroclastic explosions, have sometimes, but not always, been found to contain elevated Pt. The tephra from the Cascade Range volcanoes, which as Moore et al. note are “the closest active volcanoes upwind of White Pond,” for example do not have high Pt concentrations. They searched for volcanic tephra at White Pond but found only a few isolated and randomly distributed shards and concluded, “This negative finding indicates that the Pt anomaly at White Pond did not originate from terrestrial magmatic sources.”

Osmium

Elevated osmium, another member of the PGE group, is also a potential indicator of an ET event. Moreover, the $^{187}Os/^{188}Os$ ratio in chondritic meteorites differs significantly from that of continental crust and potentially can serve to identify the presence of an ET component.

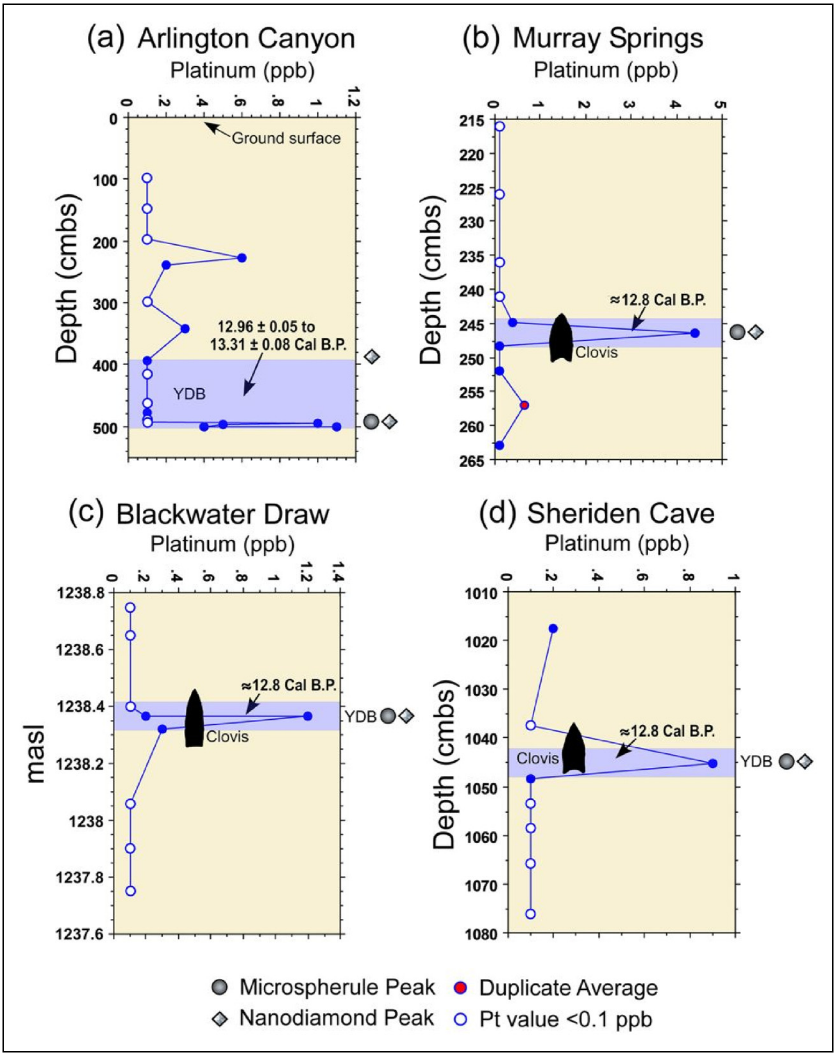


Figure 9. Peaks in platinum abundance and other event markers at four YDB sites. The arrowhead symbol indicates where Clovis-age artifacts have been found.[76] Reproduced under the terms of the CCA 4.0 International License.

Reports of osmium abundances at the YDB parallel those for iridium: some researchers found elevated amounts while others did not. Paquay et al.[71] investigated osmium abundances and isotope ratios in sediments and reported "No evidence of an extraterrestrial (ET)-PGE enrichment anomaly in any of the investigated depositional settings investigated [sic] across North America and in one section in Belgium." Bunch et al.[78] responded that Paquay et al. actually had found iridium at ">300% above background' and that although their osmium isotope ratios appeared to be terrestrial, they had not analyzed magnetic separates, which had been shown to exhibit higher iridium concentrations. Sharma et al.[79] reported ET osmium in YDB-aged Pacific and Atlantic ferromanganese crusts. Beets et al.[80] measured osmium abundances and isotopic ratios at a YDB site in the Netherlands close to the one at Lommel, Belgium that Firestone et al. included in their study. Beets et al. write,

> The Os isotope composition of 0.53 [^{187}Os/^{188}Os ratio], sandwiched between values >1.1, implies contribution of a significant amount of non-radiogenic Os. Since the pollen spectra show no reworking, the non-radiogenic Os could only have been delivered as a discrete pulse at 12.893 cal yr BP [sic]. The observation of the non-radiogenic Os isotope composition would therefore be consistent with a meteorite impact.

Sun et al.[52] reported osmium abundances and isotopic ratios from Hall's Cave, Texas, a well-studied YD site. They sampled across the YDB and concluded that the most likely source for the observed increase in osmium concentrations was "volcanic gas aerosols and not ET materials." The Laacher See eruption, they wrote, "May have triggered the temperature decline associated with YD climate change in the Northern Hemisphere." However, a high-resolution investigation of cores from Stara Jimka paleolake in the Czech Republic by Kletetschka et al.[81] had already demonstrated conclusively, by inspection of the core, that the YDB level postdates the Laacher See volcanic eruption. Sun et al. did not cite Kletetschka et al. As noted above, Petaev et al. found that "The Pt spike clearly occurs after the Laacher See volcanic eruption."[75]

As documented in their Supplemental Materials, Sun et al. collected five samples from different stratigraphic sections that they considered to represent the YDB layer in Hall's Cave. One of these samples was found to exhibit an osmium anomaly but no platinum anomaly, while another sample exhibited a platinum anomaly but no osmium anomaly. Sweatman[8] concluded, "Probably, as these five measurements were all taken laterally at the depth of 151 cm, this variation in the data reflects the slowly undulating nature of the stratigraphy of the Hall's Cave sediments and/or the 'nugget' effect. Clearly, Sun et al.'s (2020) decision to focus on the sample with the osmium anomaly is selective and unjustified." Sweatman includes Sun et al. with a group of articles of which he writes, "Even work purported to contradict the impact hypothesis, when examined closely, actually supports it."

Sun et al.[53] conducted a later study of osmium at the Debra L. Friedkin archeological site in Texas. They began by writing that "Reproducibility of these [impact] markers is challenged by failed duplication of proxy signatures at the same sites," citing Surovell et al.;[37] Paquay et al.;[71] and Daulton et al..[39] Neither of the two Sun et al. articles cited LeCompte et al.,[61] Wittke et al.,[54] and Kinzie et al.[69] which collectively had replicated the microspherule and nanodiamond evidence. Sun et al.[53] reported that "The new results here thus independently confirm that the [PGE] abundances in the unradiogenic Os layers are likely a fingerprint of volcanic gas aerosols derived from large Plinian eruptions and not extra- terrestrial materials. The results are inconsistent with the ET hypothesis and support instead an episodic and volcanic origin for the observed geochemical anomalies at the Debra L. Friedkin and Hall's Cave sites, Texas."

If volcanism were responsible for the YDB at Hall's Cave, for example, then how to explain the "nanodiamonds, aciniform soot, and magnetic spherules" reported there by

Stafford et al.?[82] One possible explanation is that in conflated and bioturbated shallow archaeological sites, volcanic signatures and impact proxies are not mutually exclusive but might occur together. As for the possibility that the YDB is volcanic everywhere, thus falsifying the YDIH, there is virtually no physical evidence of volcanism at any YDB site and several authors have rejected the possibility.[5,8,54,76,83,84]

As for the YDB nanodiamonds, Daulton[85] proposed that they could derive from mantle material, but isotopic analyses by Tian et al.[66] are inconsistent with a mantle origin. Kinzie et al. wrote, "Mantle-derived nanodiamonds have never been found in any known geological column associated with coeval peaks in impact markers, arguing against this hypothesis. [T}errestrial lonsdaleite [a form of diamond produced by high shock pressure] has never been observed in any deposits of any age in Europe or North America, where YDB lonsdaleite-like crystals are currently found."

As shown in Figure 10, Svensson et al.[86] demonstrated from Greenland and Antarctic ice cores that the platinum spike "occurs about 45 years after the volcanic quadruplet, i.e., after the Greenland cooling has initiated but before it has reached its minimum." They also showed that the platinum spike predates the next evidence for volcanism in these records by about 200 years. It is also noteworthy that no Os anomaly was found in the Greenland ice cores at the level of the Pt spike.

In summary, the platinum peak points to a cosmic event in the same way that the iridium spike at Gubbio supported an ET cause for the K-Pg mass extinction.

Is the Younger Dryas boundary synchronous?

If an ET event caused the YD, then within the limits of dating precision, the YDB will have the same age everywhere. If on the contrary, different YDB sites have different ages and especially if those ages spread over a significant amount of time, that would falsify the claim of an instantaneous event. One of the arguments brought against the YDIH was that it failed the test of synchroneity, the *sine qua non* of an ET event.

Methods for radiocarbon dating have steadily improved over the decades, with modern accelerator mass spectrometry allowing results precise to within ± 20 to ± 30 years for materials of YD age. But many factors can limit the accuracy of even the most precise radiocarbon dates.[87] These include the variation in ^{14}C concentration over time due to carbon turnover in the ocean, magnetic field variability, fluctuations in cosmic ray activity, and numerous other factors. Sampling can lead to the "old wood" effect, in which for example the age obtained is that of an ancient tree rather than that of the later campfire in which the wood burned. Because the proportion of ^{14}C in the atmosphere has varied over time, radiocarbon dates are not absolute but must be calibrated using a curve based on independently measured ages of tree rings, varves, speleothems and the like. A further complicating factor is that ages reported at different times may have been based on different calibration curves and thus cannot be compared directly. The accuracy and precision of radiocarbon dates obtained in older investigations are often lower than those measured today and in some cases the particular calibration curve used may not have been specified.

To test whether the YDB is synchronous, Meltzer et al.[47] examined the reported ages for the "supposed Younger Dryas boundary layer at the 29 sites and regions in North and South America, Europe, and the Middle East in which proponents [of the YDIH] report its

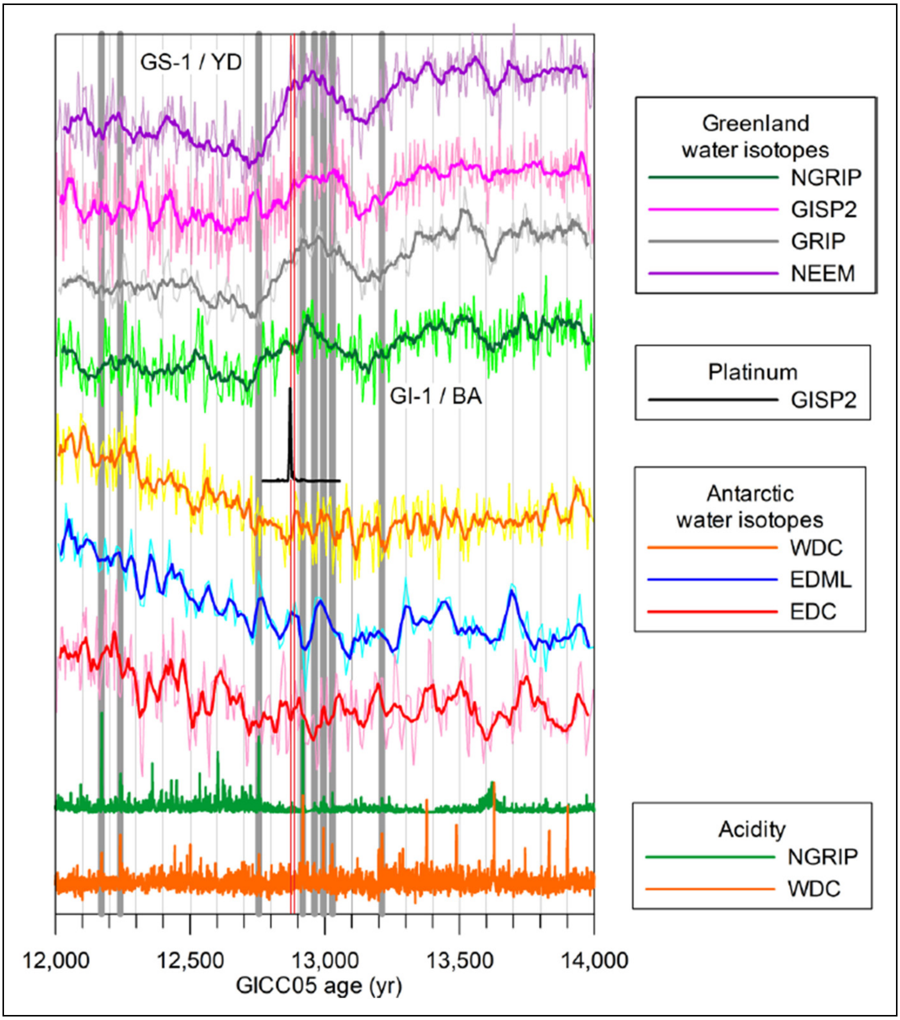


Figure 10. The platinum spike and the age of volcanic eruptions (vertical gray bands) in Antarctic and Greenland ice cores.[86] Reproduced under the terms of the CCA 4.0 international license.

occurrence." Only 3 fell within the time span defined by YDIH proponents at the time. Meltzer et al. concluded, "The YDIH fails the critical chronological test of an isochronous event at the YD onset, which, coupled with the many published concerns about the ET origin of the purported impact markers, renders the YDIH unsupported." Sweatman responded, "However, no standard errors were provided [by Meltzer et al.] for their calculations. It is therefore not possible to determine if any of these age differences are significant. In a technical sense, therefore, their data is meaningless and their conclusions cannot be supported."[8]

By the time Meltzer et al. conducted their study, radiocarbon specialists in many fields had begun to employ Bayesian analysis to compare multiple radiocarbon dates. This technique recognizes that "Calibrated ^{14}C dates have probability density functions that are not normally distributed and, therefore, many of the standard methods of classical statistics cannot be applied."[88] The method produces probability density functions in which the true age lies within a specified age range at a defined probability percentage. Shortly after the investigation by Meltzer et al. Kennett et al.[89] used the OxCal program to apply the Bayesian method to "354 dates from 23 stratigraphic sections in 12 countries on four continents to establish a modeled YDB age range for this event." As shown in Figure 11, their dataset included six independently dated "proxy records" as well as the age of the YDB platinum peak in the Greenland ice. From this study they obtained a modeled age range for the YDB of "12,835–12,735 Cal B.P. at 95% probability." Kennett et al. concluded:

> The 23 YDB age estimates appear isochronous within the limits of chronological resolution (~100 y) and could have been deposited during a single event. These findings refute the claim of Meltzer et al. that YDB ages are asynchronous. Furthermore, the ages of the YDB at 23 sites are statistically contemporaneous with the independently determined onset of the Younger Dryas climate episode, suggesting a causal link between the two. The widespread distribution of the YDB layer suggests that it may serve as a datum layer.

Since the work of Kennett et al., several new or re-studied YDB sites have been dated using Bayesian analysis (See Table 3). One test of the synchroneity of the YDB is whether these newly reported ages fall within the range reported by Kennett et al. They do.

Jorgeson et al.[51] took exception to the claim of synchroneity for the YDB. They used a Monte Carlo simulation to evaluate "the magnitude of variability expected in a ^{14}C dataset associated with a synchronous event": namely, the Laacher See eruption in Germany. Their simulation showed the Laacher See dataset to be "consistent with expectations of synchroneity." When they applied the method to the YDB dataset they had assembled from published ages, however, they found it inconsistent with "simulated expectations." This led them to conclude that their Monte Carlo simulation "call[s] into question the Younger Dryas Impact Hypothesis more generally." Sweatman[8] concluded, "Their conclusion that YDB sites are not synchronous, because the dispersion in radiocarbon dates from within the YDB layer is greater than from within the Laacher See boundary layer, is not supportable. Instead, their conclusion should have

Table 3. Radiocarbon ages from six recent studies fall within the YDB range of Kennett *et al.*

Site	Age in Cal Years B.P.	Source
23 YDB Sites	12,835–12,735	Kennett et al. (2015)[89]
Abu Hureyra, Syria	12,825 ± 55	Moore et al. (2020)[74]
Lake Hind, Manitoba	12,766 ± 61	Teller et al. (2020)[35]
Pilauco, Chile	12,770 ± 160	Pino et al. (2019)[84]
Stara Jimka, Czech Republic	12,755 ± 92	Kletetschka et al. (2018)[81]
White Pond, SC	12,785 ± 58	Moore et al. (2019)[77]
Wonderkrater, South Africa	12,744	Thackeray (2019)[90]

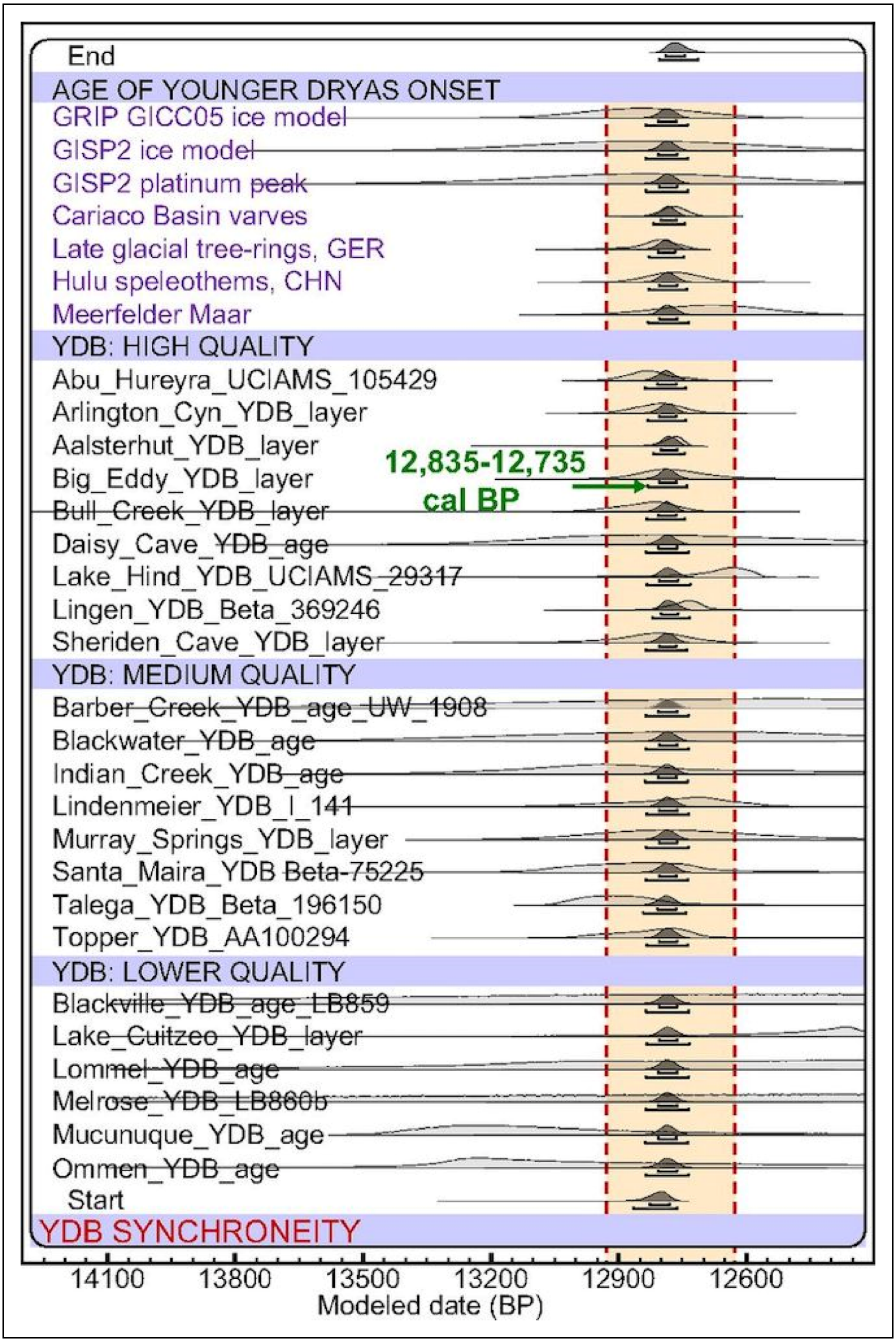


Figure 11. Bayesian synchroneity tests for the YD onset at 23 YDB sites, shown with the GISP2 platinum peak and six independently dated climate records.[89] With permission of the NAS.

Table 4. YDB boundary sites with indicated impact markers. Diamond symbols represent replication at two sites or more. PGEs stands for platinum group elements, mainly platinum itself. (Note: Some sites were not investigated for a given marker.).

SITES (56)	Location	Continent	Black Mat	Impact Spherules	Melt glass	Nanodiamonds	PGEs	Fire markers	No.	Source
Aalsterhut	NED	Eur	●			●	●	●	4	48,57,92,93
Abu Hureyra	SYR	Asia	●	◆	●	●	●	●	6	54,57,69,74,83
Arlington Cyn	CA, US	N Am	●	●		◆	●	●	5	54,57,64,69,76,91
Audenge	FRA	Eur	●	●	●	●	●	●	6	94
Barber Creek	NC, US	N Am		●			●		2	54,76
Big Eddy	MO, US	N Am		●					1	54
Blackville	SC, US	N Am		◆	●	●	●	●	5	54,57,69,83
Blackwater Dr	NM, US	N Am	●	◆			◆	●	4	5,54,57,61,62,76,95
Bull Creek	OK, US	N Am				◆	●	●	3	54,57,68,69
Caspian Sea	ASIA	Asia	●	●	●	●	●	●	6	94
Chobot	AB,Can	N Am	●	◆		●		●	4	5,54,63,69,96,97
Daisy Cave	CA, US	N Am	●			●		●	3	57,69
Dengtiltis	LITH	Eur					●		1	98
Flamingo Bay	SC, US	N Am					●		1	76
Gainey	MI, US	N Am	●	●			●	●	4	5,54,95
Guil-Mt.Viso	FRA/IT	Eur	●	◆	●		●	●	5	54,99–101
Halls Cave	TX, US	N Am	●	●		●	●	●	5	53,82
Howard Bay	NC, US	N Am		●			●	●	3	5
Indian Creek	MT, US	N Am	●		●	●		●	4	57,69,102
Johns Bay	SC, US	N Am					●			76
Kangerlussuaq	GRL	Eur				◆		●	2	65,69
Kimbel Bay	NC, US	N Am		●				●	2	54,57
Kolb	SC, US	N Am					●		1	76
Krokslys	LITH	Eur					●		1	98
Lindenmeier	CO, US	N Am	●			●		●	3	57,69
Lingen	GER	Eur	●	●		●		●	4	54,57,69
Lk Cuitzeo	MEX	S/C Am	●	◆		◆		●	4	54,57,67,69
Lk Hind	MT,Can	N Am	●	◆		◆	◆	●	5	5,35,64,69,71,96,97

(Continued)

Table 4. (continued)

SITES (56)	Location	Continent	Black Mat	Impact Spherules	Melt glass	Nanodiamonds	PGEs	Fire markers	No.	Source
Lk Medved.	Russia	Asia					●		1	103
Lommel	BEL	Eur	●	◆		◆	◆	●	5	5,49,54,57,66,69,80,93,95
Lopaiciai-2	LITH	Eur					●		1	98
Lutterzand	NED	Eur	●				●		2	98
Melrose	PA, US	N Am	●	◆	●	●	●	●	6	54,57,69,83,95
Morley	AB,Can	N Am	●	●					2	5,96,97
Mucunuque	VEN	S/C Am	●	●	●		●	●	5	27,28,57
Murray Spgs	AZ, US	N Am	●	◆	●	◆	◆	●	6	5,26,54,57.63,69,71,75,83,95,104
Myrtle Bay	SC, US	N Am					●	●	2	5,57
Newtonville	NJ, US	N Am	●	●		●	●	●	5	54,57,61,69,95
Ommen	NED	Eur	●	●		●		●	4	54,57,69
Paijan	PERU	S/C Am	●	●	●	●	●	●	6	94
Parangueo Lake	MEX	S/C Am		●				●	2	57,105
Paw Paw Cove	MD, US	N Am		●					1	61
Pen Point	SC, US	N Am					●		1	76
Pilauco	Chile	S Am	●	●			●	●	4	84
Santa Maira	SPN	Eur	●			●		●	3	57,69
Sheriden Cave	OH, US	N Am	●	◆		◆	●	●	5	54,69,76,95,106–108
Squires Ridge	NC, US	N Am		●			●	●	3	76
Stara Jimka	CZE	Eur		●				●	2	57,81
Talega	CA, US	N Am	●	●				●	3	54,57
Topper	SC, US	N Am		◆		●	●	●	4	5,54,57,61,63,69,76
Ula-2 outcrop	LITH	Eur					●		1	98
Velnio Duobes	LITH	Eur					●		1	98
Wally's Beach	AB, Can	N Am		●			●		2	5
Watcombe	UK	Eur	●			●		●	3	69
White Pond	SC, US	N Am					●		1	77
Wonderkrater	RSA	Africa					●		1	90
Total		**56**	**30**	**34**	**10**	**26**	**38**	**39**		

been that the Younger Dryas and Laacher See events are not equivalent, which is an obvious result." Moreover, to reject the YDIH because of a Monte Carlo simulation ignores the large amount of well-reported and otherwise unexplainable physical evidence of an ET event.

The evidence shows that YDB sites are synchronous within the ± 100-year precision of the Bayesian method. Thus the YDIH survives a test that otherwise could have falsified it.

Summary of cosmic impact evidence at the YDB

Though we have focused on the early rejection of the YDIH, it is useful to take stock of where the evidence stands today and to understand what led Sweatman[8] to suggest that the hypothesis may merit promotion to the status of theory. Table 4 brings up to date and summarizes the YDB impact event-markers that researchers have reported at 56 YDB sites worldwide.

The sites listed in Table 4 range over more than half the Earth's surface and surely do not represent the most distal occurrences of the YDB. They cover an area as large or larger than that of the strewnfield of Australasian tektites, which have long been attributed to impact and for which scientists have recently discovered a potential source crater.[110,111] No crater of YDB age has been found; the 31-km Hiawatha Crater in Greenland could be of YD age but has not yet been directly dated.[112]

Conversion

Prior to the scientific revolutions of the 1960s, very few opponents of continental drift, meteorite impact cratering, and anthropogenic global warming ever publicly changed their minds. Many senior scientists never did, carrying their opposition to the grave. In the case of the YDIH, however, it is notable that one of the foremost authorities on the YD changed his mind and said so.

In a 2010 article,[24] the late Wallace Broecker had noted that, "The recent suggestion that the Younger Dryas was triggered by the impact of a comet has not gained traction," concluding that "there is no need to call upon a one-time catastrophic event to explain the YD…[as] it was a necessary part of the last termination." In a later unpublished "Broecker Brief"[109] on his website, undated but post the 2013 discovery of the platinum spike in the Greenland ice,[75] he described how he came to change his mind:

> When the Firestone et al. scenario first appeared, I was shocked by its grandiose claims, i.e., the comet did-in the Clovis people, it created a fire extending over at least two continents, it was the cause of the extinction of large mammals in North America.… Then when it was shown that there were no Bucky Balls [the fullerenes reported by Firestone et al.] and no iridium spike, I joined many others scorning this idea. Later when, as part of a Nova TV show, the claim was made that nano-diamonds were present at the YD onset in an outcrop of Greenland ice, I backtracked a bit. But as questions regarding the occurrence of nano-diamonds cropped up, I relapsed to my negative stance.

(As noted above, fullerenes have not been shown to be absent at the YDB; Broecker's statement may reflect a false impression based on the wording of the Pinter and Ishman article. As for iridium, some found it elevated at the YDB while others did not, so this point should have been moot.)

Broecker went on to write:

> The Greenland platinum spike makes clear that an extraterrestrial impact occurred close to the onset of the YD. Although I don't for a minute believe that this impact did in the mammoths and the Clovis people, I do think that it triggered the YD.
>
> I realize that this subject is distasteful to many because of the early false claims. But the new evidence suggests that there was some kind of extraterrestrial impact. Hence it should be given further study.

But as we have seen, it was the early claims of irreproducibility that turned out to be false.

Cause and effect?

Firestone et al. proposed that a cosmic impact had "contributed to YD cooling, major ecological reorganization, broad-scale extinctions, and rapid human behavioral shifts at the end of the Clovis Period." These effects are integral to the YDIH in the same way that the Alvarez Theory encompasses not only the impact, but its effect on life on Earth. The following findings suggest that the impact hypothesis may better account for the changes associated with the YD than the traditional explanations.

YD cooling and changes in ocean circulation

- The temperature changes at the beginning and end of the YD cool episode were unusually abrupt, taking place on the scale of years and possibly even a single year.
- The temperature change was unusually pronounced, reaching temperatures near those of the Last Glacial Maximum.
- The YD onset coincides with the Pt spike in the Greenland ice and the accompanying change in oxygen isotope ratios there.
- The YD began as Earth's astronomical pacemaker was causing warming.
- The destabilization of Lake Agassiz, Baltic Ice Lake, and the Greenland ice margins, as well as the "great plumbing shift" that ended drainage from Lake Agassiz south down the Mississippi River, all occurred at or close to the start of the YD.
- The strongest cooling took place at the beginning of the YD rather than at the end, contrary to most other Pleistocene temperature oscillations.[113]

The pleistocene megafaunal extinction

- Grayson and Meltzer report that only 15 archeological sites "provid[e] compelling evidence for human involvement in the death and/or dismemberment of five genera of now-extinct late Pleistocene mammals: Equus, Camelops, Cuvieronius, Mammut, and Mammuthus."[114] They were "highly skeptical that human overkill was responsible for their extinction."
- Only one kill-site, Wally's Beach in Southern Canada, has evidence of human involvement together with bones of horses and of camels.[115,116]
- At some sites the black mat, coeval with the start of the YD, drapes over the bones of megafauna whose remains are never found in younger strata. For these species, the extinction occurred at the same time as the start of the YD. At Murray Springs, they include the American Lion, Short-faced Bear, Camel, Horse, Mammoth, Mastodon, Tapir, and Dire Wolf.[26]
- Could small bands of Paleo-Indians, armed only with spears and atlatl with a range of a few-score feet, have hunted the horse to extinction in the Western Hemisphere, where it roamed in vast herds numbering in the untold millions, all while leaving next to no physical evidence of the carnage?
- In North America, 72% of megafaunal genera above 44 kg went extinct, while in South America 83% did.[117] In a recent article, Prates and Perez used the Sum Probability Distribution method to track the change in density of large mammals and of Fishtail projectile points (FPP), which resemble those of Clovis, at South American archeological sites.[118] Their results are shown in Figure 12.

Prates and Perez write:

- The radiocarbon signal of large mammals around 18 k cal BP is extremely low in South America, but clearly increases from 17,5k cal BP, and grows rapidly and steadily between 15,3 and 12,9 k cal BP. After 12,9 k cal BP, the SCPD curve shows a dramatic decline until 11,6 k cal BP. From this date onwards, only a few genera of extinct large mammals have been recorded and most of the alleged early Holocene dates have recently been called into question. Fishtail projectile point technology shows a rapid amplification of density until reaching the distribution peak between 12,4 and 12,2 k cal BP…. From this time onward, a deep decline continues until the technology virtually disappears.
- Pino et al. note that in southern Chile and in Antarctica, the temperature change at the YD went from colder-to-warmer.[84] It is hard to argue that temperature change in opposite directions could have caused similar megafaunal extinctions in each hemisphere.

The fall of Clovis

- Evidence has been growing that the Clovis were not the first to populate the Western Hemisphere. Bennett et al. have now reported convincing evidence that humans were present in North America at today's White Sands National Park, NM, at the

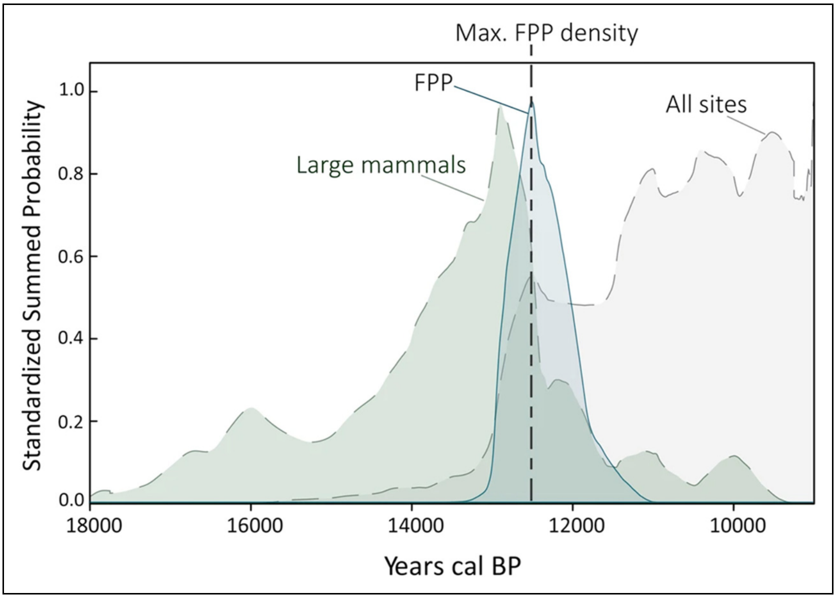


Figure 12. The inferred change in the density of large mammals (light green shading), FPP (light-blue shading), and archeological sites (beige shading) reflected for all of South America. Reproduced under the terms of the CCA 4.0 International License.

Last Glacial Maximum "~23 and 21 thousand years ago."[119] During the ten millennia until the YD, people survived many changes in climate. After 10 millennia, neither humans nor animals would have been "naive" with respect to the other.

- By ~ 13 ka, Clovis had become the dominant culture across North America, yet lasted only a few hundred years at most. Just at its prime, Clovis suddenly fell.
- No Clovis artifacts have ever been found in place above the YD.
- In the Southeastern US, near the onset of the YD, the Clovis suddenly abandoned a dozen Paleo-Indian chert quarries. At the Topper site, LeCompte et al. found impact microspherules touching Clovis artifacts, but no microspherules below the artifact layer.
- In the eastern US, Clovis artifacts have been found from Maine to Florida, where average yearly temperatures differ by much more than the ~10°C change at the beginning of the YD. Could such a relatively small temperature change, even one that occurred rapidly, by itself have destroyed such a well-adjusted and widespread culture?

These findings collectively suggest that a sudden external trigger launched the YD and contributed to the cooling, the extinction, and the Clovis disappearance. As Haynes noted, "Stratigraphically and chronologically the extinction appears to have been catastrophic, seemingly too sudden and extensive for either human predation or climate change to have been the primary cause."[26] One can turn the question around and ask whether a cosmic event with effects spread over half the Earth's surface would not have affected Pleistocene climate, Western Hemisphere megafauna, and Clovis culture.

Conclusion

It should have been clear to readers, including peer reviewers, that Pinter and Ishman had offered hyperbolic language but no actual evidence against the YDIH; that Surovell et al.[37] had failed to sample the YDB and/or made fatal errors in procedure; and that the samples reported by Scott et al.[40] and used by Pinter et al.[7] and Daulton et al.[49] had not come from the YDB and therefore did not bear directly on the impact hypothesis. Instead of critically examining and rejecting these false claims, many geologists and impact specialists embraced them, thereby allowing an alleged absence of evidence to trump abundant, peer-reviewed evidence, even photographic evidence. Then a kind of "groupthink" seems to have set in, rendering the YDIH beneath further consideration.

The broader lesson from impact cratering, continental drift, anthropogenic global warming, and now the YDIH is that it is better to encourage further research than to prematurely condemn a novel, data-based hypothesis to the dust bin of science. Unfortunately, once a hypothesis has been prematurely rejected, even truly "extraordinary evidence" may not be enough to restore it to scientific respectability.

Finally, we can now assess Sweatman's suggestion that the YDIH may be ready for promotion from hypothesis to the status of theory. If we combine the definitions of "theory" from the National Academy of Sciences and the American Association for the Advancement of Science, it would read something like this:

> A scientific theory is a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence. One of the most useful properties of scientific theories is that they can be used to make predictions about natural events or phenomena that have not yet been observed.

Those who have read this article and Sweatman's have the information to decide whether the YDIH meets this definition. In this author's opinion, there is a strong case that it does. Moreover, it should not be forgotten that no other single theory can explain the YD and its associated effects.

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Note

1. No microspherules were found in the first set of samples collected at Lake Hind. But they were found in a second set as reported by Teller et al.[35]

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